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14. ABSTRACT

An annular field reversed configuration (AFRC) plasma translation experiment is under development at the Air Force Research Laboratory (AFRL). This experiment (referred to as XOCOT-T) is a preliminary investigation on using AFRC's as a high power electric propulsion technology. As such, the focus of this experiment is to measure the translation of AFRCs formed at low (2 kV) voltages and on diffusive timescales. XOCOT-T's experimental design is based on previous work done at AFRL with AFRC plasma formation studies (known as the XOCOT). Upgrades to the design include a 3-turn, conical outer electromagnetic coil, a pulsed gas feed system, and a new vacuum facility. A suite of high power pulsed diagnostics used in this study include electrostatic Faraday probes, magnetic field probes, a wide angle photometer, and a magnetic flux loop. In this paper, hardware developments and initial results of plasma formation and translation studies will be presented.

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Initial Results on an Annular Field Reversed Configuration Plasma Translation Experiment

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An annular field reversed configuration (AFRC) plasma translation experiment is under development at the Air Force Research Laboratory (AFRL). This experiment (referred to as XOCOT-T) is a preliminary investigation on using AFRC's as a high power electric propulsion technology. As such, the focus of this experiment is to measure the translation of AFRCs formed at low (2 kV) voltages and on diffusive timescales. XOCOT-T's experimental design is based on previous work done at AFRL with AFRC plasma formation studies (known as the XOCOT). Upgrades to the design include a 3-turn, conical outer electromagnetic coil, a pulsed gas feed system, and a new vacuum facility. A suite of high power pulsed diagnostics used in this study include electrostatic Faraday probes, magnetic field probes, a wide angle photometer, and a magnetic flux loop. In this paper, hardware developments and initial results of plasma formation and translation studies will be presented.

I.   Introduction: FRCS for Propulsion

To meet the demand for next-generation high power electric propulsion systems, the Air Force Research Laboratory is actively investigating field reversed configuration (FRC) plasmas. These plasma formations are high power density compact toroids that are easily translated from their formation chamber. They've been a long-stay in the fusion community since their debut in 1958[1] and offer significant promise to the spacecraft propulsion community for high power electric propulsion. Their inherent ability to operate at high power levels makes them more suitable for high thrust-to-power and higher total propellant throughput for high power and large mass spacecraft than traditional propulsion methods. Additionally, their high beta value and near unity conversion of thermal to kinetic energy promise increased efficiency.

Fundamentally, an FRC is a charge-neutral, dense, hot plasma compact toroid, which is formed by a magnetic field reversal in a theta-pinch coil. The reversal forms a closed, self-consistent magnetic field structure which the wraps around the plasma. This closed configuration is well-suited for formation, increased heating, and ultimately translation. Translation studies have shown that FRCs can translate up to 15 m in a guide field without significant degradation.[2] Translation velocites of 170 km/s in deuteruim have been obtained.[3]

The initial concept of forming FRC plasmas at spacecraft-adaptable power levels has recently been demonstrated by AFRL/University of Michigan[4].[5] This program, referred to as XOCOT, was successful in producing coherent formations at voltage levels below 1 kV. The experiment in this paper, the XOCOT-T, is a next-generation device of the XOCOT and is used to demonstrate plasma translation.

II.   Background: Annular Field Reversed Configuration

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Field reversed configuration plasmas have seen significant benefit from over 50 years of design heritage. Improvements in stability, lifetime, and scaling laws have been made. A paper by Tuszewski[6] contains a comprehensive overview of much of this research. Traditional FRCs are formed at voltage levels (200 kV) and on timescales (5 μs) that are not available on spacecraft. While efforts have been extended to form FRCs at lower voltages and on longer timescales, the majority of FRC research has focused on the traditional formation. The low voltage studies include the Rotamak[7] and the Coaxial Slow Source (CSS)[8].[9] Additionally, previous propulsion studies on FRCs have been conducted by NASA Marshall's high-voltage, high-specific impulse plasmoid thruster concept (PTX)[10] and by the University of Washington's STX fusion propulsion concept.[11]

The CSS is the most appealing low-voltage FRC formation technology for propulsion applications, owing in part to it's simple geometry. While insufficient for fusion due to low temperatures, the CSS concept has demonstrated FRC formation at coil voltages of less than 2 kV and discharge times longer than 250 μs. The XOCOT geometry is based upon the general geometry of the CSS device, but is scaled to incorporate lower discharge voltages. As stated previously, the pre-ionization and formation sequence of AFRCs in the XOCOT has been successfully demonstrated.[4]

Annular FRCs are formed in a different manner than their traditional FRC predecessors. Rather than using a large field reversal, a diamagnetic current is induced in the plasma. Figure 1 illustrates the formation sequence for an annular geometry. The formation sequence begins by filling the discharge channel with a neutral gas and lightly pre-ionizing it. Then, a large current is applied to the inner and outer coils. The current on the outer coil generates a diamagnetic current in the plasma and the inner coil adds bias flux. The field lines on the ends of the plasma, where the plasma is the weakest eventually tear and reconnect to form the closed field structure. Then, additional external flux can be added to further heat and compress the plasma. Once the plasma becomes detached from the external field, it can be translated out of the main discharge chamber.
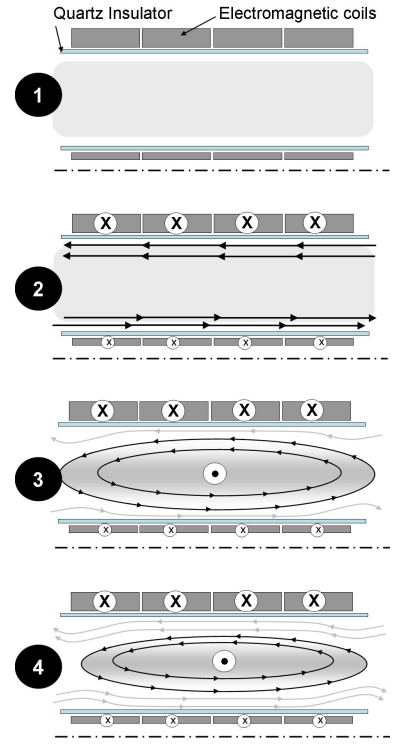

Figure 1. AFRC Formation Sequence.

A. Translation FRC physics

Translation is a well-studied mechanism with FRCs,[12],[3].[13] The fusion community's primary interest in translation is that it allows the plasma to be formed in a separate region and then translated into a compression chamber. FRC translation in this paper was done using a conical discharge coil. In this configuration, a radial field component interacts with the aziumuthally induced plasma current, resulting in an axially directed Lorentz force on the plasma. The cone angle is essential to formation and translation; it must be great enough so the plasma can overcome the natural mirror created on the wide end of the coil, yet it must be small enough to contain the plasma for sufficient formation.

III. Experimental Apparatus

The main discharge chamber for the XOCOT-T is similar to the original XOCOT in that it uses a set of coaxial coils surrounded by quartz liners. However, the XOCOT-T contains several upgrades to the original hardware, including smaller coil diameters and mounting to a background vacuum facility. The experiment is mounted to AFRL's Chamber 5B in a horizontal configuration. For these experiments, the background pressure in Chamber 5B was 1×10^{-5} torr. The outer coil is a stepped, conical 3-turn coil (13.5" on the small diameter) to faciliate translation and increase magnetic flux. The cone angle for the outer coil is nominal $5°$ [a]. The inner coil is a 4-turn, segmented aluminum coil that is 5" in diameter. It is cantilevered off an aluminum back plate, which contains several vacuum feedthroughs. The quartz insulators stand off the coils by 1/2 inch to accomodate probe access. Figure 2 displays the side view of the discharge chamber and a solid, cross-sectional model showing the stepped cone configuration.

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[a]An alternate configuration of $1.6°$ was also tested. These experiments, however, were unsucessful in plasma translation

(a)   (b)
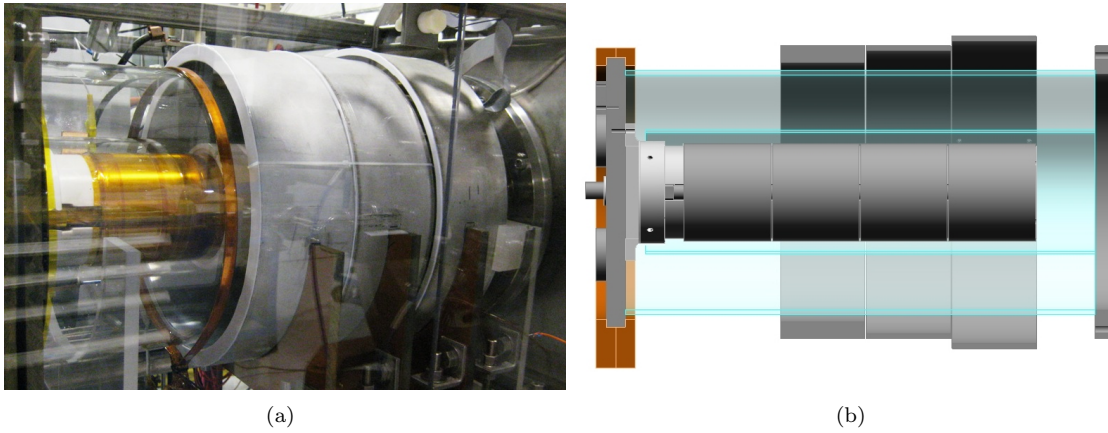
Figure 2. XOCOT-T experimental facility and cross-section.

Pre-ionization of the initial plasma is accomplished using a separate external coil, formed to the outer quartz insulator. The coil is made from thin, copper strap shaped into a saddle, straddling both ends of the main discharge coil to create a uniform pre-ionization discharge. The 0.1 μF capacitor bank that powers this coil is switched through a thyristor 100 μs before the main bank discharge. A high voltage DC glow provides the seed ionization required for breakdown.

The electromagnetic switching network for the XOCOT-T uses much of the exisiting hardware from the XOCOT, with the exception of a new main capacitor bank and improved transmission lines. The main bank is a 22-kV, 225 μF high energy capacitor. The transmission lines for the main bank are constructed from solid copper bus bar to minimize resistance and inductive losses. Inductive losses are further minimized by running the forward and reverse lines on top of each other. Figure 3 is a photograph of the switching network, including both the pre-ionization and main capacitor banks.

Another upgrade to the XOCOT-T from the XOCOT is the addition of a high speed gas puff valve. This valve is a Series 9 Miniature Pulse Valve. With an external valve driver, it can be driven to operate in 160 μs. For this experiment, the valve was driven with a single ampltitude square pulse; the opening time was observed to be 0.8 ms. Argon was the working gas in this paper, although tests were also done with Xenon.
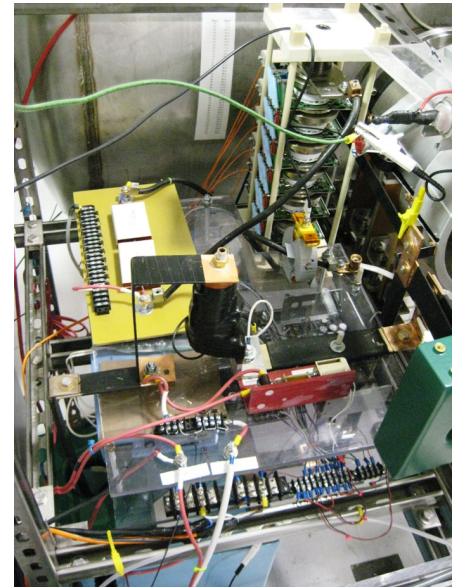

Figure 3.   XOCOT-T switching network.

A.   Device Operation

The timing sequence of the XOCOT-T was investigated to determine optimal device operation. Three events need to happen in succession:

1. The pulse valve opens and remains open for t_{puff}.

2. The pre-ionization bank triggers, resulting in a ringing current through the pre-ionization coil.

3. The Main Bank triggers, pulsing current through the coaxial main discharge coils.

IV.   Diagnostics

Several diagnostics were employed to take measurements on the XOCOT-T. This included a suite of external diagnostics: current monitors, external magnetic field (b-dot) probes, a flux loop, and a wide angle

photometer. Figure 4 describes the diagnostic setup. The external diagnostics used in this experiment are identical to the ones used in the XOCOT. For the sake of brevity, consult Kirtley's thesis[4] for complete descriptions on these diagnostics. The internal diagnostics employed in this experiment was limited to a pair of Faraday probes.
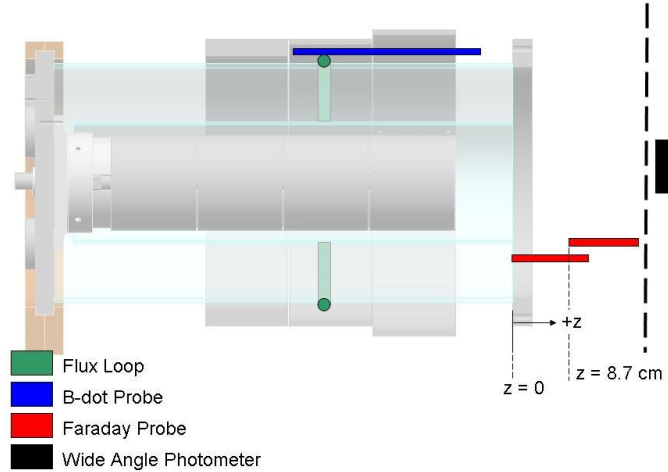

Figure 4. XOCOT-T diagnostics.

A. Internal Faraday Probes

A pair of indentical Faraday probes were constructed to take downstream measurements of the FRC. Traditionally, Faraday probes are used to measure current density of a flowing plasma. In this case, however, the Faraday probes were used to obtain a qualitative measure of plasma translation and time-of-flight (TOF). The Faraday probes were constructed from aluminum, machined to a diameter of 0.24". The probes were sealed inside of a ceramic liner and coated with a non-conductive cement paste so that only the face of the probe was exposed to the plasma. Figure 5 shows the construction of one probe and how the probes were positioned inside the vacuum tank.[b] Both probes were biased to -31 V to collect maximum ion current.

Figure 5. Faraday probe.

V. Parameter Investigation

The initial tests of the XOCOT-T focused on developing a test matrix of operating parameters. These parameters are shown in Table 1 below. Since the XOCOT-T was able to use the fundamental concepts learned from XOCOT, the pre-ionization voltage and the main bank trigger were fixed at their optimal parameter as shown. The XOCOT discharged into a static gas backfill; the XOCOT-T had the added complexitity of a gas puff valve.

Each parameter was tested by setting all other parameters to their nominal setting. In most cases, excluding the gas puff, this nominal setting was chosen as the minimum value required for device operation. The gas puff, it was determined, had little effect on overall performance. For this reason, it was fixed at 7 ms, although 5 ms and 3 ms could have been used with similar results.

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[b]Note that although three probes are shown in the photo, the third probe, located the furthest downstream is not used in this paper.

Table 1. XOCOT-T Test Parameters.

Operating Parameter	Test Range	Nominal Condition
Main Bank Operating Voltage	500 V - 3.0 kV	2.5 kV
Pre-Ionization Bank Operating Voltage	6.0 kV (fixed)	6.0 kV
Glow Discharge Voltage	5.0 kV (fixed)	5.0 kV
Gas Puff Length	1 ms - 11 ms	7 ms
Gas Pressure	20 psi - 100 psi	30 psi
Pre-Ionization Trigger	1 ms - 10 ms	5 ms
Main Bank Trigger	100 μs (fixed)	100 μs

VI.   Results and Discussion

The data reviewed in this section is limited to the photometer data, the Faraday probe data, and the data from the magnetic field probes. The photometer is used to show qualitative plasma formation. Peaks in the photometer data indicate plasma formation and their ampltitude scales roughly with increased plasma compression (pressure and temperature). The Faraday probe data captures plasma current moving past the probe. It is expected that FRCs arriving at the probes will appear as sharp, severely pointed peaks spanning a few microseconds. Data showing wide, well-rounded features would seem to indicate a bulk thermalized plasma. Lastly, the magnetic field probe (B1) used in the first 3 sections is set near the end of the coils close to the translation region. This data has been analyzed to show only the deficit field, or the field contributions due strictly to the plasma. In most of the sections, only data for the first 3 FRCs are shown. FRCs formed after 300 μs are complicated with the previously translated plasma reflecting off the walls and traveling back towards the discharge chamber as well as interactions with background gas.

A.   Nominal Operating Conditions

The experiment was conducted six times at nominal operating conditions to determine repeatability from pulse to pulse. As was found with the XOCOT,[4] each test is exceptionally repeatable at fixed conditions. Figure 6 describes the results from the Faraday probes.

(a) Faraday Probe 1
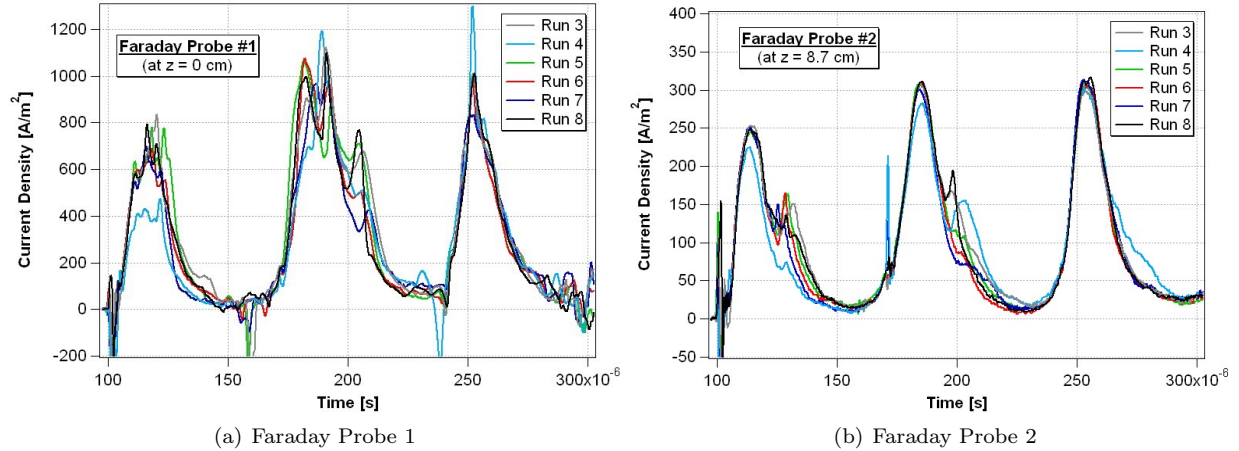
(b) Faraday Probe 2

Figure 6.   Faraday probe data at nominal operating conditions.

The data taken on the other diagnostics is not shown here, but was exceptionally repeatable from pulse to pulse, deviating at most by 5 percent from average. The Faraday probe data is somewhat less consistent, as the probes are likely more sensitive to noise than the other 2 diagnostics. However, for both Faraday Probe 1 and Farday Probe 2, the waveforms recorded by the probes are fairly repeatable.

B. Pressure Effects

The back pressure behind the pulse valve was varied from 20 psi up to 100 psi with the rest of the parameters fixed at their nominal condition. By increasing the pressure at the valve, the mass flow rate of propellant into the discharge channel increases. The lowest pressure for plasma formation was found to be 30 psi; the plasma failed to form at 20 psi. Figure 7 shows the results.

From the wide angle photometer in Figure 7, it can be seen that as the gas pressure increases, the plasma increases in brightness, which can be correlated to an increase in compression, temperature, and density. This trend is most obvious in the darker spots of the photometer data (i.e. valleys). This effect is also seen in the deficit magnetic field data. As the gas pressure is increased, the magnetic pressure in the plasma also increases, indicated by an increasing magnetic field in the plasma.

It is difficult to see the effects of pressure in the Faraday data for the first part of the discharge (peaks 1 and 2). It is obvious that pressure changes the plasma structures arriving at the Faraday probes considerably. The 3 distinct peaks seen in the Faraday probe 1 data on the 2nd FRC formation at 30 psi take on rounded irregular structures above 40 psi. Beyond the 2nd FRC formation (after 225 μs) the current density increases significantly with pressure and the peak of the data shifts later in time. It appears that the plasma translating from the discharge channel becomes impeded by a large mass of slower moving ions and neutrals already ejected from the discharge channel. It mixes with the slow moving background gas to create complicated ion populations around the probes. Also, the current density never drops back down to zero at high pressures and later times. The magnetic fields at this point have significantly weakened and it appears that the discharge channel begins to stream hot gases. This indicates an inefficiency that scales with pressure; more energy is being used to heat the gas than is being put into translation.
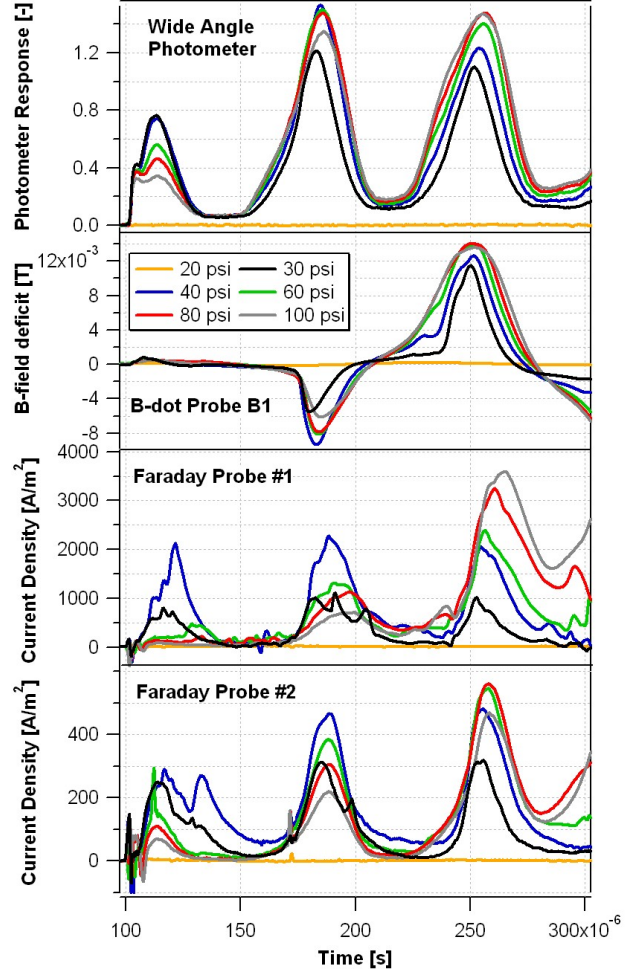

Figure 7. Pressure effects.

C. Timing Sequence Results

The timing sequence consists of letting in a puff of gas and then ionizing it right as the front wave of gas reaches the end of the discharge coils. If the ionization is triggered too late, not only will propellant leave the channel without being ionized, but cold background gas will fill the translation region. This will mix with and cool the translating FRC. The gas timing sequence was empirically tested by adjusting both the puff valve open time and the pre-ionization delay. The puff valve open time was varied from 1 ms up to 10 ms. The pre-ionization delay (the time between the gas valve opening time and the pre-ionization trigger) was varied from 1 ms to 11 ms. Figure 8(a) shows the results from the puff valve timing on the first 3 FRC formations, while Figure 8(b) displays the effect of the pre-ionization delay for the entire sequence.

This data indicates that while there is a certain threshold of gas required for FRC formation, additional gas volumes beyond the lower limit do not alter either the formation or translation of the FRC appreciably. With the XOCOT-T, it was found that a 3 ms delay between the initiation of the gas puff and the pre-ionization of the plasma is the minimal requirement for reliable operation. Also, the addtional gas let in after the ignition of the pre-ionization bank appears to collect behind the FRC and has little effect on the

formation or translation mechanisms. Therefore, it is desired to keep the gas puff as short as possible to minimize wasting propellant. From these data sets, it appears that the critical timing parameter is the pre-ionization delay. As the pre-ionization delay increases, more cold gas appears to pile up just beyond the exit of the FRC. When the plasma leaving the discharge channel impacts it, it causes the same type of broad structures that were seen in Faraday probe data during the gas pressure study at elevated pressures (Figure 7). As was explained previously, the hot dense plasma leaving the chamber mixes with this downstream gas and ionizes portions of it. This effect is extremely pronounced in the later stages (after 300 μs) in the Faraday probe 2 data where huge plasma clouds appear on the data. This is undesirable as this detracts from plasma translation and instead goes into ionizing cold gases downstream.
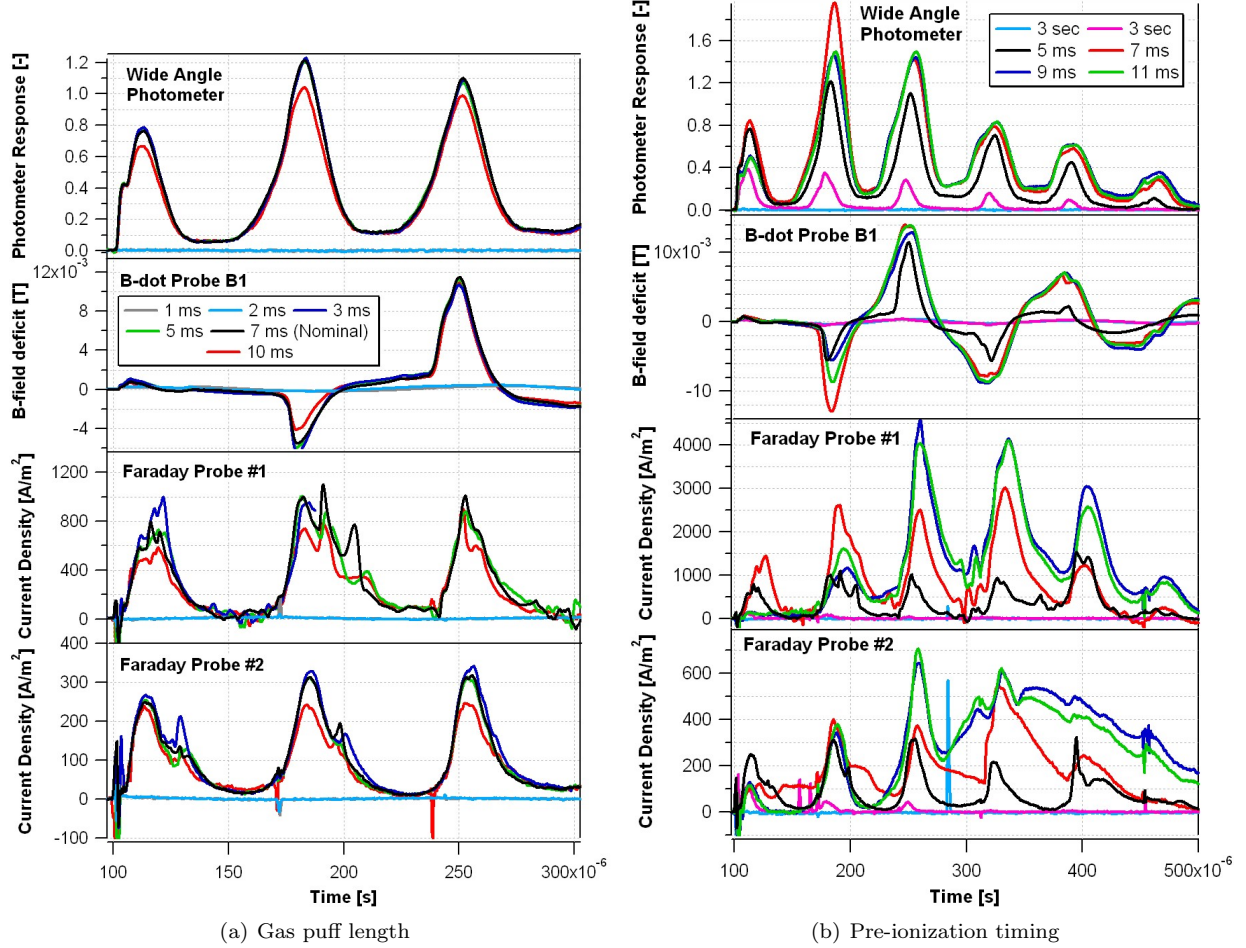

(a) Gas puff length

(b) Pre-ionization timing

Figure 8. **Effect of timing parameters on FRC formation and translation.**

D. Preliminary Translation Results

Figure 9 shows an overlay of the data from the axial b-dot probes, the Faraday probes, and the wide angle photometer at nominal operating conditions for the second and third FRC formation only. The data has been peak normalized. From this time-history, it is apparent that plasma structures are moving out of the discharge channel and into the background chamber. A magnetized structure first registers on the 3 axial magnetic field probes, then a bulk plasma structure arrives at the Faraday probes a short time later. While this would suggest that an FRC is being translated out of the channel, the data is not overwhelmingly conclusive.

Temperature and density measurements are not available for the XOCOT-T. The analysis in this section, therefore, is completed using the peak plasma parameters from the XOCOT experiment.[4] The XOCOT
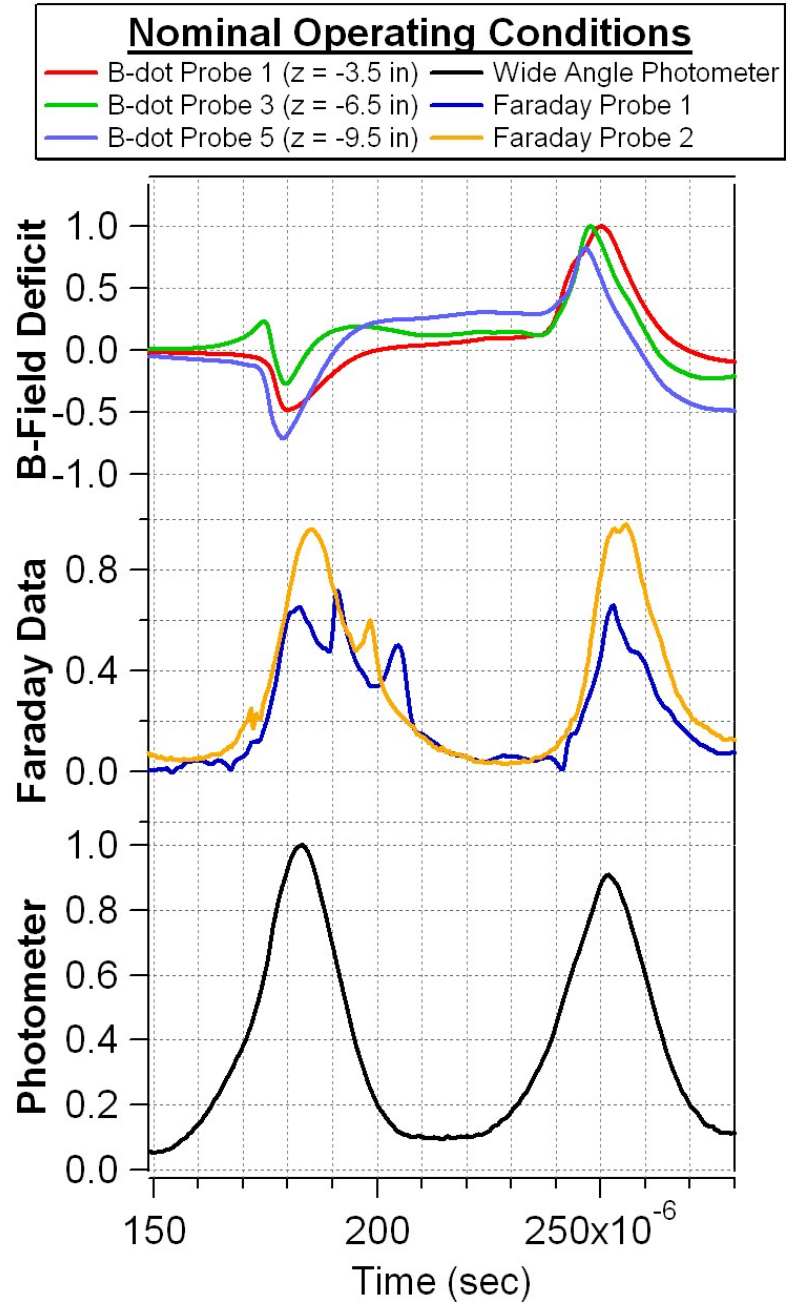
Figure 9. Normalized Translation Data

measured a peak plasma temperature around 10 eV, and a peak density of $10^{19} m^{-3}$. It is reasonable to assume that a bulk 10 eV population would have a high energy tail with a significant fraction of ions having a temperature in excess of 40 eV. From conservation of energy, the maximum velocity an argon FRC can achieve at these parameters corresponds to it's maximum thermal energy such that for a 40 eV plasma, the maxiumum velocity an FRC can reach is 22 km/s. In relation, 10 eV corresponds to a maximum thermal velocity of 11 km/s.

1. Magnetic Flux Results

Ideally, time-of-flight data on magnetic field probes would show sharp, distinct peaks on each probe as the peak field of the FRC moved past. The peak separation, therefore, would indicate the plasma velocity. While sharp, defined peaks are apparent in the magnetic field probe data collected in this experiment and shown normalized in Figure 10, it seems that rather than providing insight into translation, they instead correspond to the FRC formation. They show an FRC that is growing and expanding quickly, on the order of 80 km/sec. It can also be noted that the sharp peaks shown in Figure 10 and in other magnetic field data throughout this paper indicate a highly, magnetized, well-formed FRC.
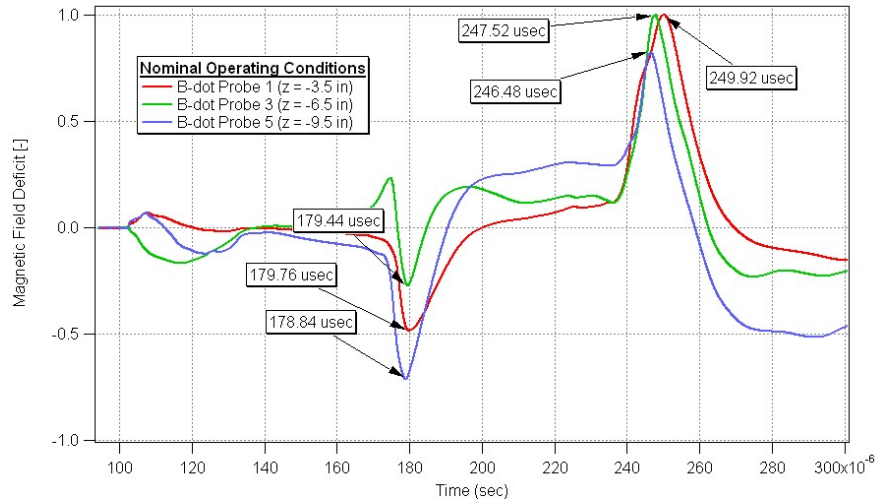

Figure 10. Translation Magnetic Field Probe data

2. Faraday Probe Results

The length of the FRC in this experiment should be similar to the coil length, about 33 cm long. Traveling at 22 km/sec, it should pass a Faraday probe in about 15 μs. The Faraday data, also shown in Figure 11, shows that the bulk of the signal picked up by the Faraday probe by a single plasma translation lasts for about 20 μs, comparable to this transit time. This is only the width of the majority of the signal; the data shows that once this bulk plasma has passed, the Faraday probes are still recording a non-zero current density around the probe.

By comparing the arrival peaks on Faraday probe 1 and 2, a bulk plasma velocity can be roughly estimated. Figure 11 shows the second peak of the formation at several different shots. The structure of this data is less reliable than the magnetic field probes, as the peak heights and positions change somewhat from shot to shot. For this reason several shots are overlayed on this plot. By picking out the most probable leading peaks on the Faraday probe data, the velocity of the translating plasma can be estimated at 26 km/s. While this velocity is on the order of the expected maximum thermal velocity, it is higher than expected. Using this method for time-of-flight, it is difficult to discern what the peaks structures seen on the probe relate to physically in the plasma. Ionization processes and collision events with downstream gas as well as FRC expansion and cooling complicate the overall plasma structure. The fast risetimes of the probes, however, indicate that a hot plasma structure is traveling rapidly downstream; from this data, it is apparent that the XOCOT-T is producing a hot, high speed plasma.
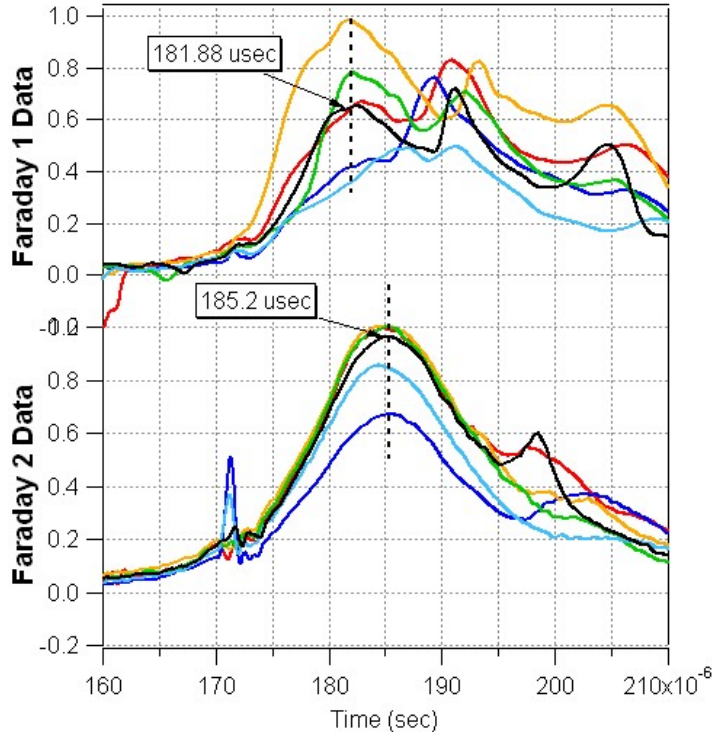
Figure 11. Translation Faraday Probe data

It is of interest to examine the shape of the structures in the Faraday probe data. The signal on Faraday probe 1 is composed of 3 distinct peaks that are all about 6 μs wide. Once the structure reaches Probe 2, it has formed a fairly uniform population, with a single peak and broad 20 us distribution. The structure on probe 2 is unexpected; it was thought that the data picked up on probe 2 would be similar to the data on probe 1, with a decrease in amplitude. Based on evidence seen in an FRC translation experiment (FRX-C/T) at Los Alamos National Laboratory,[12] it appears that the FRC is colliding with background gas shortly after being ejected from the discharge chamber. These events were also noted in previous sections of this paper. As was speculated in the FRX-C/T experiment, as an FRC translates into a background gas, plasma from the open-field-line region escapes the FRC confinement and ionizes the background gas downstream such that the plasma translates into a cold plasma, rather than a neutral gas. This effect will appear on a downstream probe as a rounded, broad plasma structure as the FRC becomes enveloped in plasma cloud. This effect was seen on Faraday probe 2 data in (shown in 11) and in the interferometery data on the FRX-C/T.

This explanation for peak structure is substantial but not entirely conclusive. The plasma densities and temperatures in the FRX-C/T were much greater than that seen in the XOCOT. While somewhat blurred, the translating FRC in the FRX-C/T was quite distingushable from the surrounding plasma since it's overall density did not change significantly. In the XOCOT-T, the amplitudes of Faraday data between probes 1 and 2 show a dramatic drop, indicating a significant drop in plasma density and/or velocity. Another factor could be contributing to the complicated downstream plasma forms seen on the Faraday probes and to the disappearance of the sharp peaked structures seen in the downstream plasma. To date, no information on FRC translation into a field free region is available; it is unknown how rapidly an FRC will expand once it hits a field free region. It is possible that the plasma could be expanding before it reaches the Faraday probe array, impacting the quartz liner in the process. This could fragment the FRC, resulting in a indiscernable, turbulent plasma mixture. Future translation measurements on an FRC should, at minimum, incorporate a magnetic field probe to determine what portion of the translating plasma is a magnetized FRC and what is a hot, thermal plasma.

VII. Conclusion

This results seen in this experiment show the effects of pressure and timing sequences on an FRC formed in an annular coil, as well as device repeatability. From these studies, the optimal operating parameters for this experiment were determined. Additionally, this experiment sought to provide preliminary translation evidence for an AFRC. While large amounts of uncertainty remain regarding the plasma translation velocity, it is apparent from the data presented in this paper that the XOCOT-T is creating a highly magnetized, hot plasma which is propogating downstream at a high velocity, on the order of the ion thermal velocity (22 km/s). It was postulated that the plasma from the discharge channel lends to the ionization of downstream gases, such that data measurements of peak FRC movement become obscured. Most importantly, though, this experiment demonstrated that while an FRC was formed and plasma was translated from the discharge channel, the plasma arriving downstream could not be confidently determined to be an FRC. Improvements in facilities and diagnotics tools are necessary for further FRC translation studies.

VIII. Future Work

The XOCOT-T was an excellent test demonstration for plasma formation and translation with the conical coil arrangement. However, new technology improvements can be implemented to further reduce system losses, reduce system maintenance, to allow for new diagnostic tools, and to better facilitate plasma translation. A second version of the translation experiment is currently under construction in Michigan Technological University's Ion Space Propulsion Laboratory. This experiment, the TeXOCOT, is slated to replace the XOCOT-T as the Air Force's AFRC translation experiment. TeXOCOT will operate at a slightly different set of operating conditions than the XOCOT-T, in an attempt to further reduce the overall dimension of the XOCOT and XOCOT-T. Additionally, the TeXOCOT will be connected to a vacuum facility that will allow a plasma to translate a longer distance (up to 4 m) and into a lower background pressure. The design will also incorporate a flux conserving region directly after the coils to ensure that the plasma formed in the discharge channel will not impact the quartz liners before arriving into the main vacuum facility.

Further work in AFRC translation studies needs to address developing an accurate time-of-flight measurement array that will build a better understanding of AFRC translation and expansion. This should include, at minimum, a suite of electrostatic probes along with magnetic field probes. Additionally, more information is required about internal structure and properties of the plasma to understand how the free expansion of an AFRC will impact it's overall performace as a thruster.

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